Post-additive manufacturing machining operations applied to Ti6Al4V biomedical alloy

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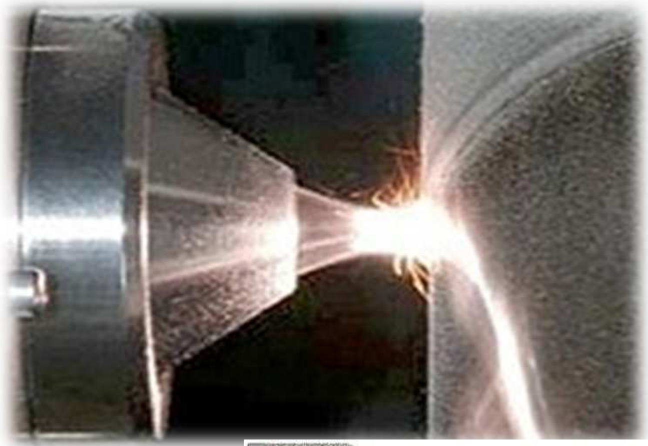
Content

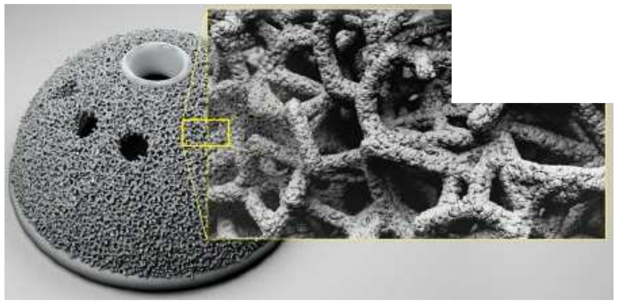
- Industrial problem & scientific background
- Ti6Al4V obtained by Additive Manufacturing technologies
- Machining tests
  - Varying cutting parameters
  - Varying lubricating/cooling strategy
- Results
  - Crater and flank wear
  - Surface integrity
  - Wear resistance in human-like environment
- Conclusions & Outlook

Motivation /1

- ***Additive Manufacturing (AM) technologies*** have been increasingly adopted to produce near-net-shape metal parts in small batches, i.e. in the biomedical field to produce tailored surfaces with osseo-integration capabilities

- ***Semi-finishing and/or finishing machining operations*** are still required to obtain adequate geometrical tolerances and surface characteristics on functional surfaces





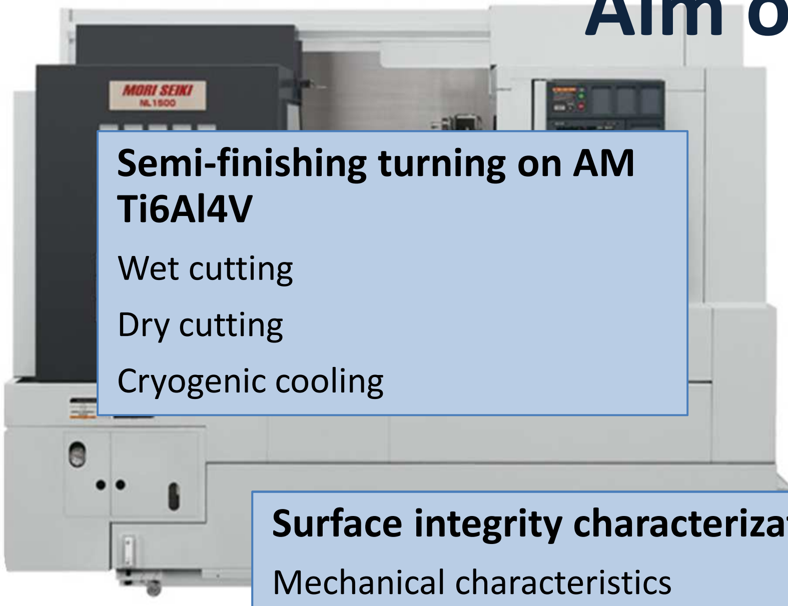
Motivation /2

- Machining operations are commonly carried out adopting standard lubricating strategies, i.e. oil mist, mineral and water emulsions
- Cleaning and sterilization of the surgical implants imply costly and time-consuming steps

Clean cooling strategies?

Which impact on the component's service life?

Aim of the research

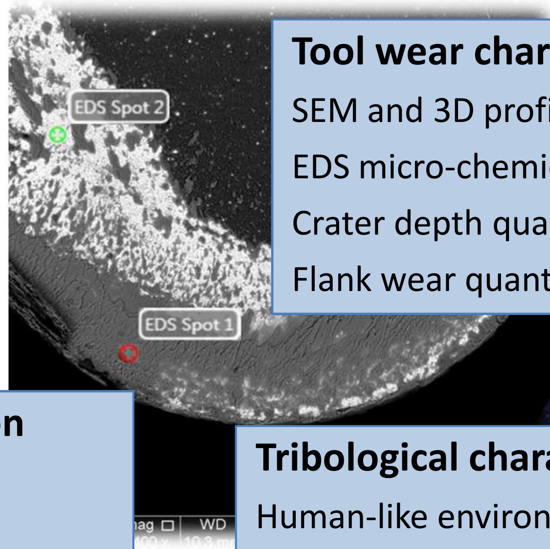


Semi-finishing turning on AM Ti6Al4V

Wet cutting

Dry cutting

Cryogenic cooling



Tool wear characterization

SEM and 3D profiler analysis

EDS micro-chemical analysis

Crater depth quantification

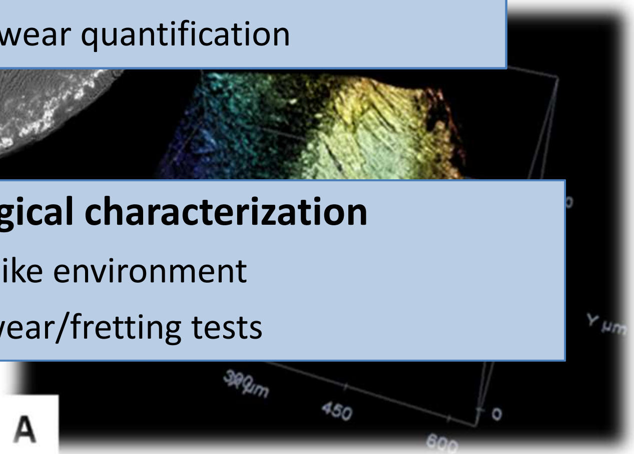
Flank wear quantification

Surface integrity characterization

Mechanical characteristics

Surface quality (roughness, defects)

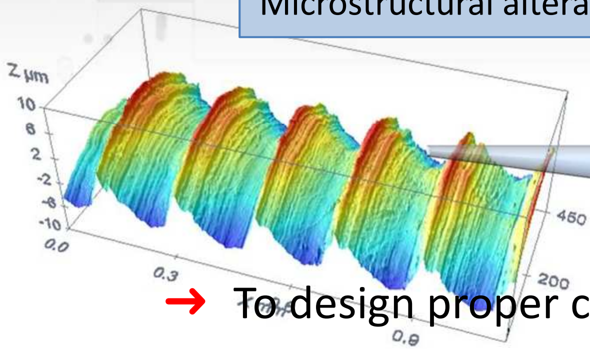
Microstructural alterations



Tribological characterization

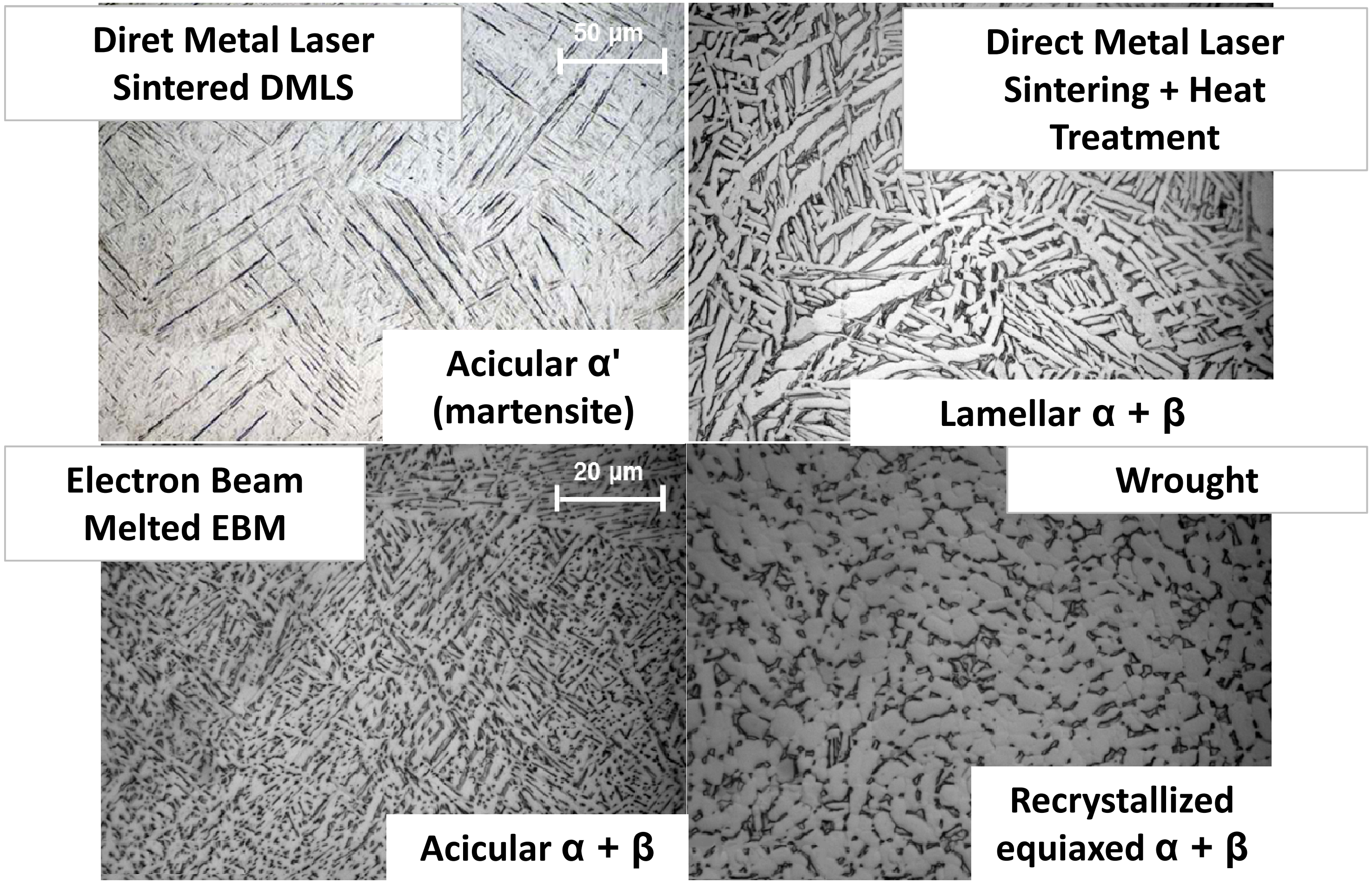
Human-like environment

Sliding wear/fretting tests



→ To design proper cutting parameters and prove the effectiveness of ***cryogenic cooling*** in reducing the tool wear and increasing the surface integrity

Material: AM Ti6Al4V /1



Material: AM Ti6Al4V /2

Ti6Al4V	E [GPa]	UTS [MPa]	Y [MPa]	Elongation [%]
Wrought	118	940	870	15
EBM	114±5	914±5	830±5	13.1±0.4
As-built DMLS	110±5	1095±10	990±5	8.1±0.3
Heat-treated DMLS	110±1	915±5	835±5	10.6±0.6

1° ISSUE

→ Which is the effect of varying cutting parameters on the tool wear and machined surface integrity under conventional lubricating conditions?

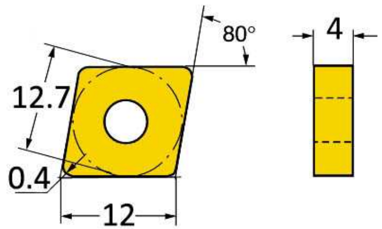
Baseline: wrought Ti6Al4V

Case study: EBM Ti6Al4V

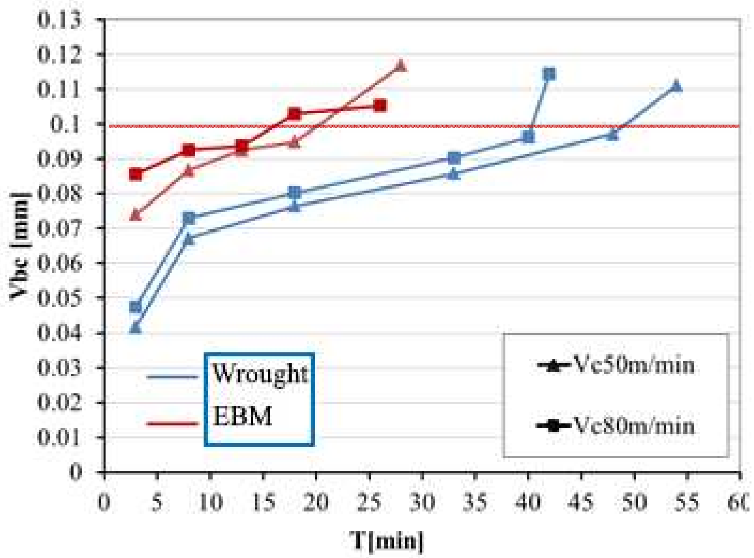
Semi-finishing turning tests

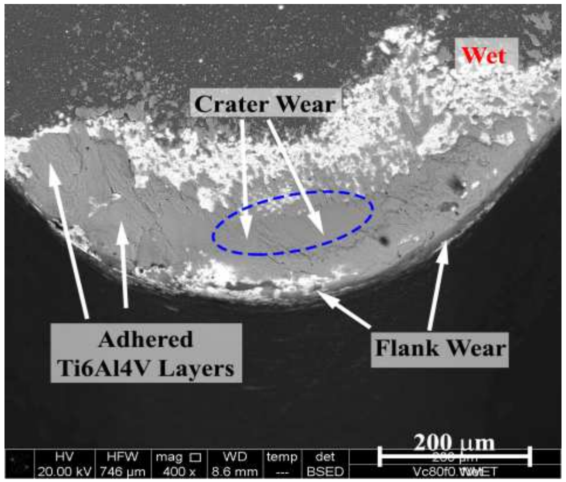
- Mori Seiki ™ NL 1500 CNC lathe
- Semi finishing TiAlN coated tungsten carbide insert Sandvik® CNMG 120404SM GC 1105
- Conventional lubricated conditions: mineral oil and water emulsion supplied at 6 bar
  - ➠ VB fixed, 0.1 mm
  - ➠ Max cutting time, 15 minutes

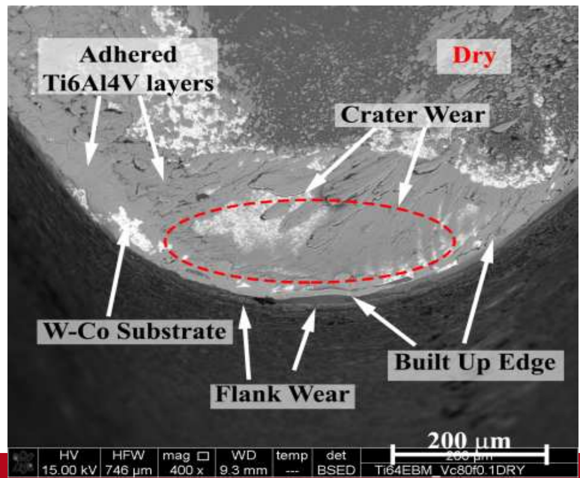
Time length [min]	Cutting speed [m/min]	Feed rate [mm/rev]	Depth of cut [mm]
3-8-15	50	0.1	0.25
3-8-15	50	0.2	0.25
3-8-15	80	0.1	0.25
3-8-15	80	0.2	0.25



Wear analysis – EBM vs. wrought





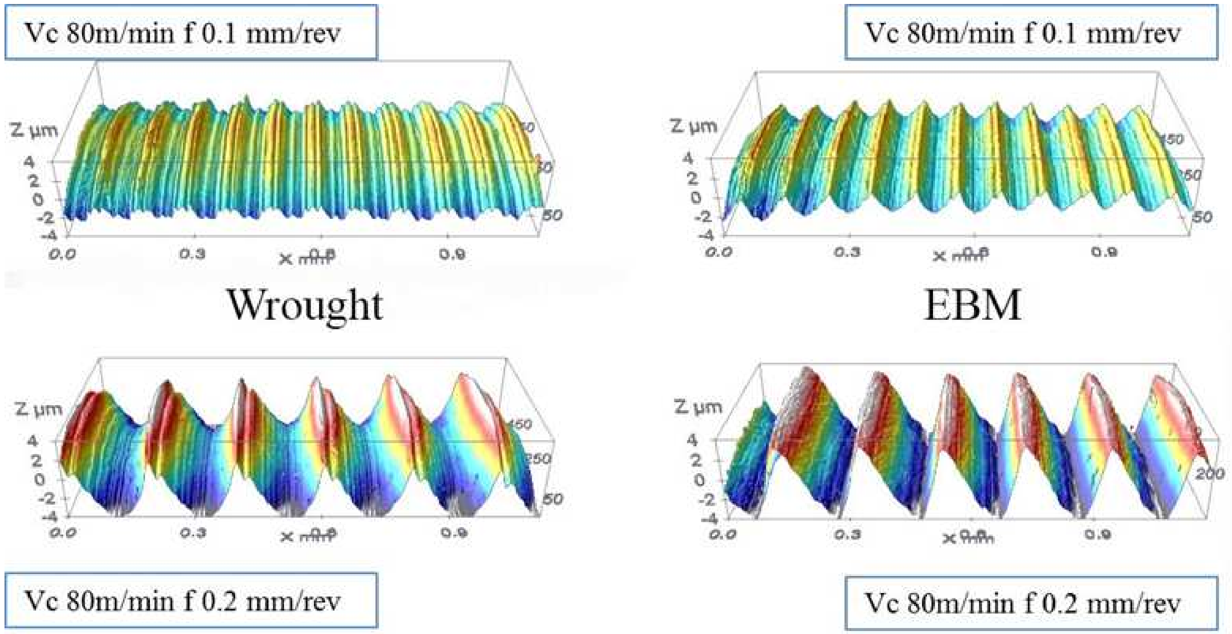


- For both the wrought and EBM alloys, the effect of the cutting speed on the tool wear is negligible
- The feed rate plays the major role

- The time to reach the tool wear limit is more than 200% in turning the wrought Ti6Al4V than the EBM Ti6Al4V for both the cutting speeds

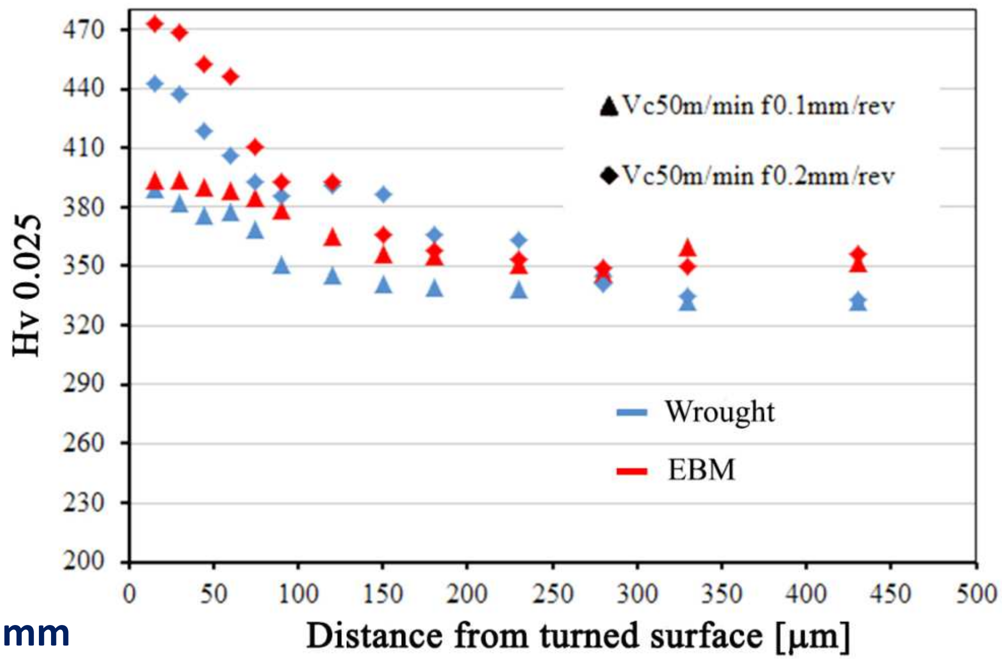
- The great amount of adhered material plays as a protection layer against the cutting speed rubbing effect

Surface topography– EBM vs. wrought



- The tool wear did not affect the surface profiles for both the alloys and for all the cutting conditions
- Material side flow and deformation along the feed marks were observed for all the cutting conditions
- Double feed marks generated at a feed rate of 0.1mm/rev , due to the lower chip thickness
- The increase of the feed rate resulted in a better surface topography due to the higher chip thickness and less smearing aside of plastic material under the tool nose

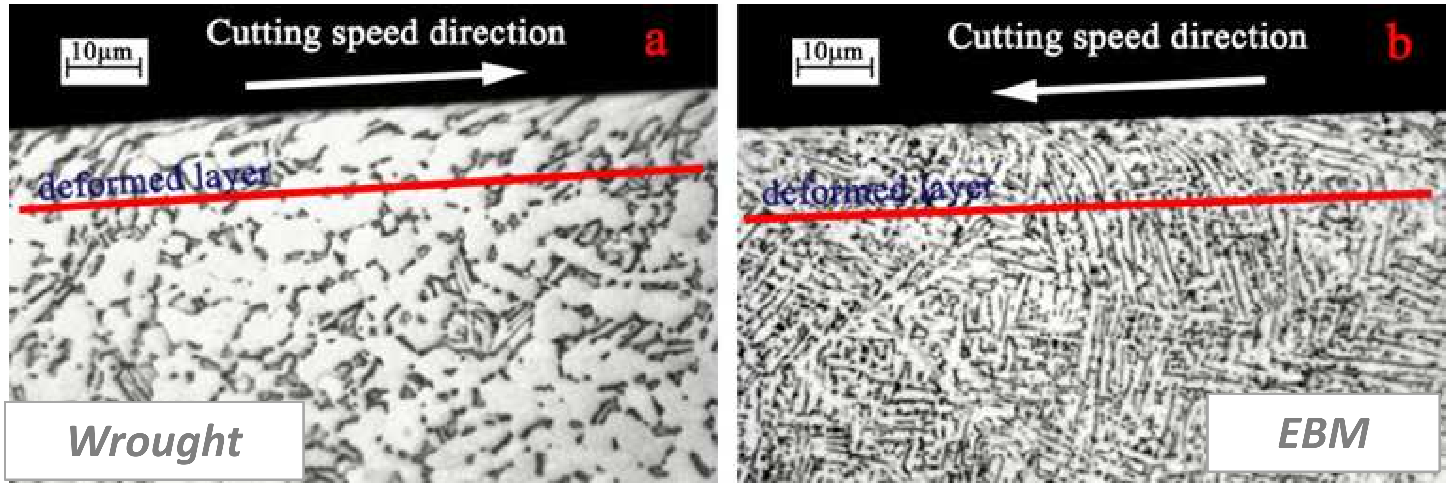
Micro-hardness– EBM vs. wrought



At VBc 0.1 mm

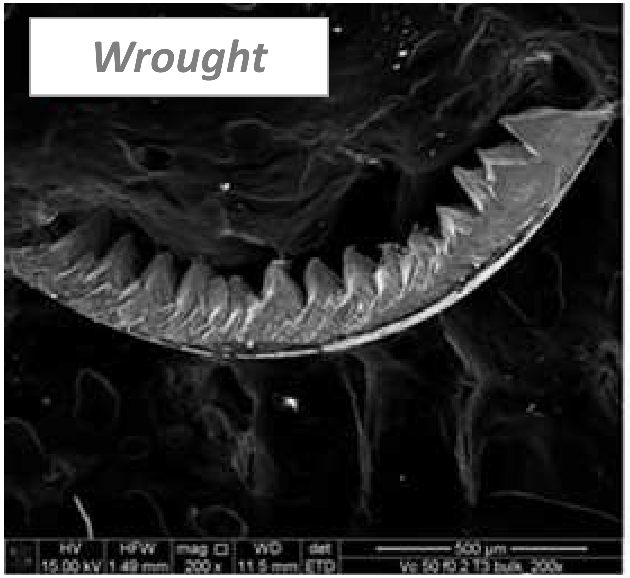
- Surface hardening along a radial direction was observed for both the alloys and cutting conditions
- Up to 100 hardness increase was measured for a feed rate of 0.2 mm/rev for both the alloys
- Higher levels of surface micro-hardness was measured at increasing cutting parameters, although the effect of the cutting speed was almost negligible

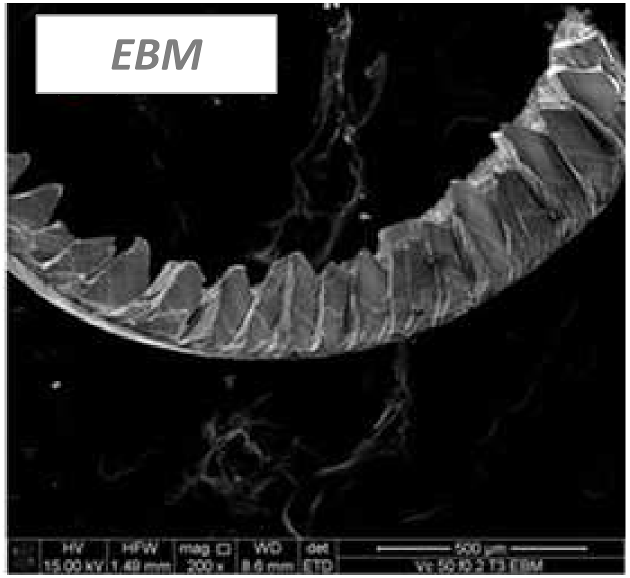
Microstructural alterations – EBM vs. wrought



- A 20 mm depth deformed layer was formed along the cutting speed direction for both the alloys
- The depth of the deformed layer did not change with the cutting parameters and was comparable for both the alloys
- The adoption of a new tool resulted in no deformed layer in the first stages of turning for all the cutting conditions and for both the alloys

Chip morphology – EBM vs. wrought





- ***Segmented chip*** resulted for all the cutting conditions when turning the wrought Ti6Al4V
- At increasing the cutting parameters, in particular for a feed rate of 0.2 mm/rev, the chip of the wrought Ti64 was more periodic
- The EBM Ti6Al4V saw tooth chip was more sensitive to the cutting parameters and at the initial stages of turning adopting a cutting speed of 50m/min and feed 0.1 mm/rev a transitional chip was observed

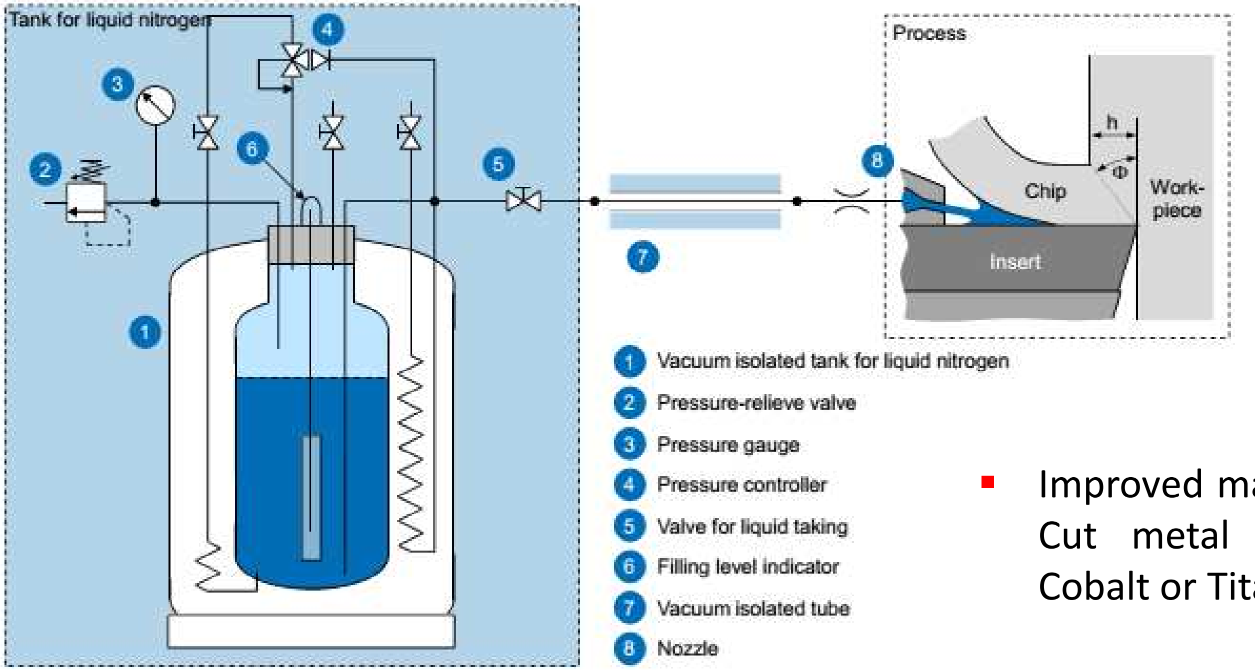
2° ISSUE

→ Which is the effect of clean lubricants/coolants on the tool wear and machined surface integrity?

Baseline: wrought Ti6Al4V

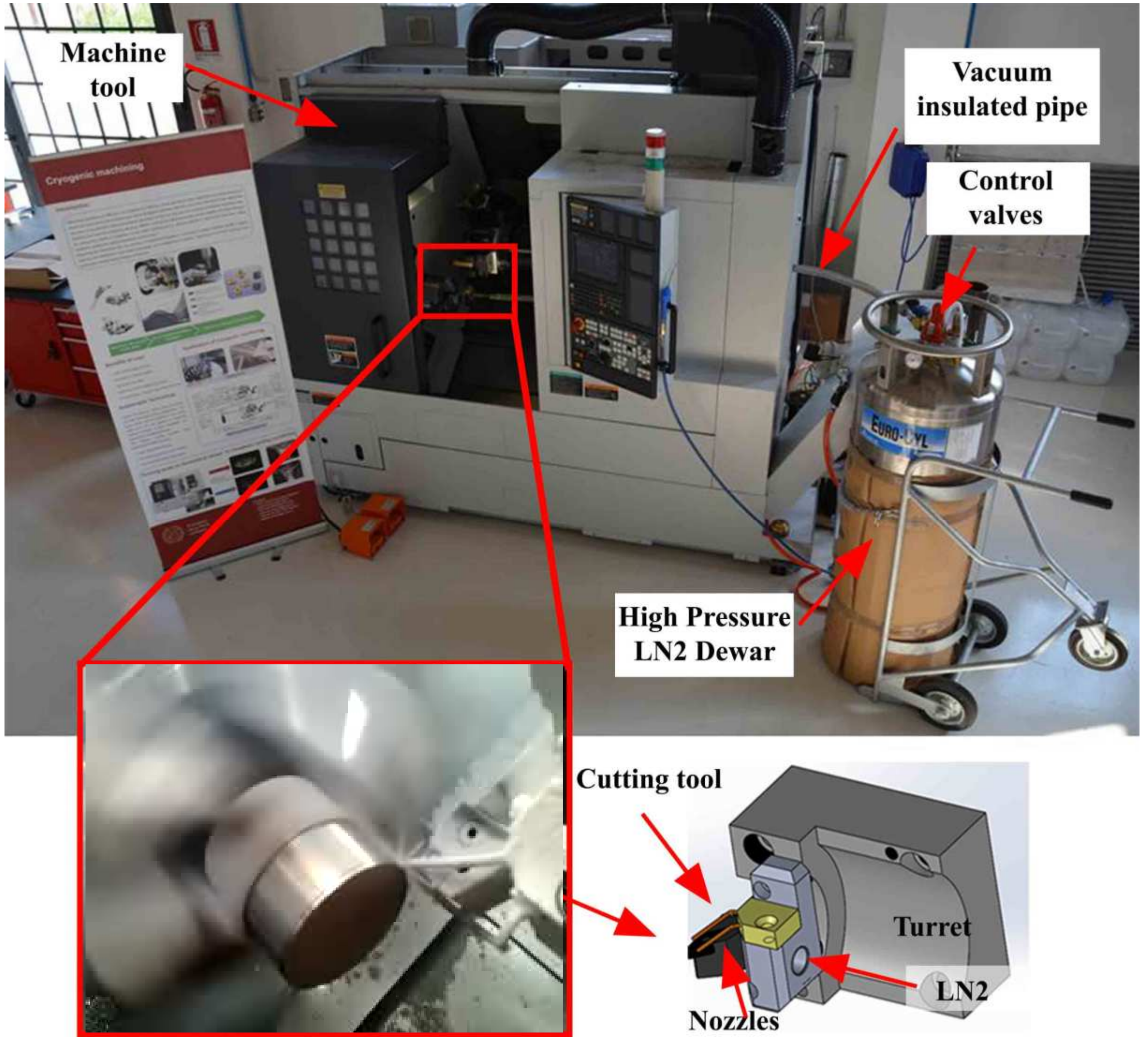
Case study: different AM variants of Ti6Al4V

Cryogenic machining - the concept



- Improved machinability of Difficult to Cut metal alloys such as Nickel, Cobalt or Titanium alloys
- Cleaner, safe, environmental-friendly strategy
- Reduced costs for cleaning and sterilizinig operations of machined surgical implants

Cryogenic machining - the implementation



- 15 minutes of turning
- Sandvik WC inserts with a TiAlN coating

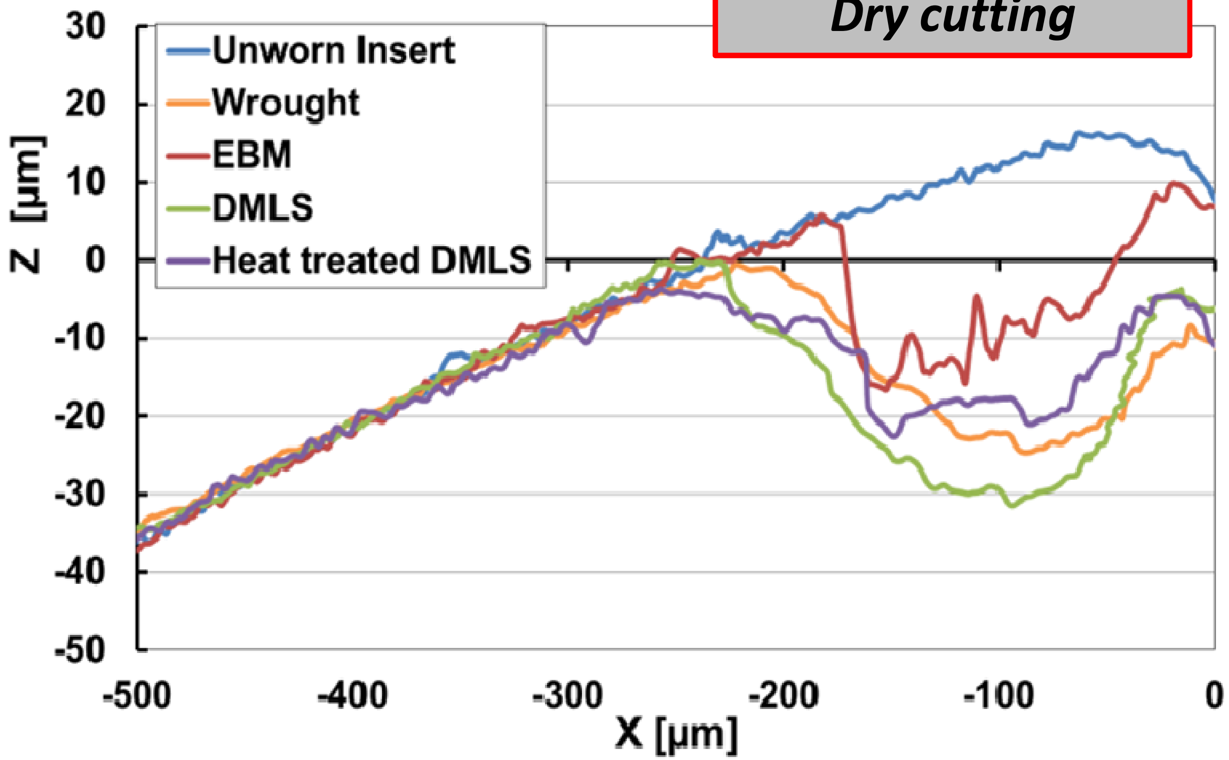
- ***Dry cutting*** and ***cryogenic cooling*** *(LN2 at 10 bars)*

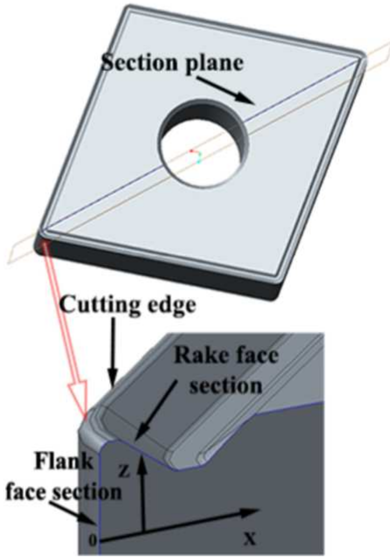
V [m/min]	f [mm/rev]	doc [mm]	Cutting strategy
80	0.2	0.25	dry
80	0.2	0.25	cryo

Crater wear /1

- ✓ Cratering always present regardless the Ti6Al4V microstructure under dry cutting, the worst when cutting the as-built DMLS material

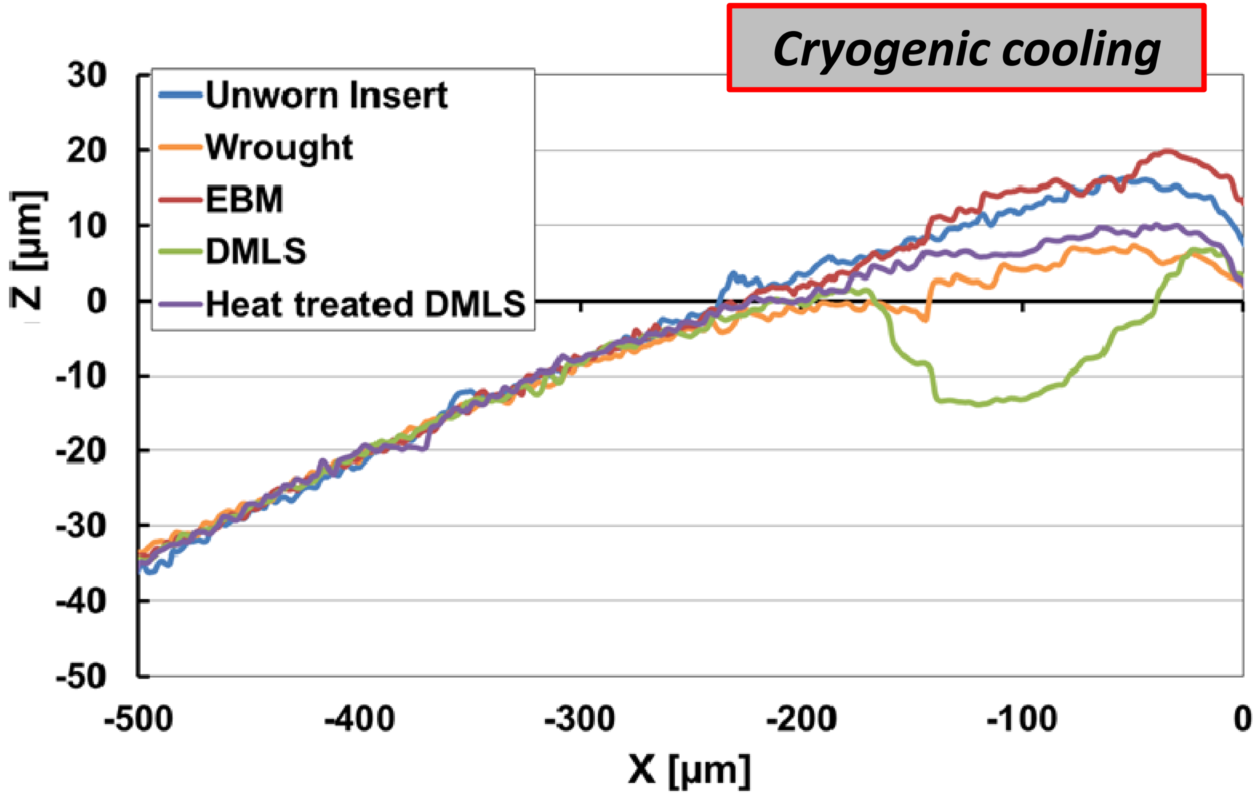
Dry cutting

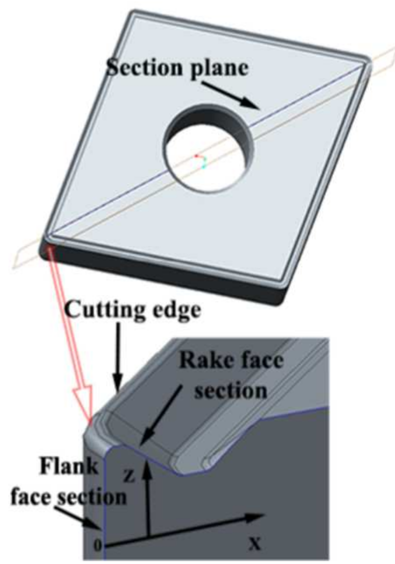




Crater wear /2

- ✓ Cryogenic cooling strongly reduced the cratering, being completely eliminated when cutting the EBM material, but still significant when cutting the as-built DMLS

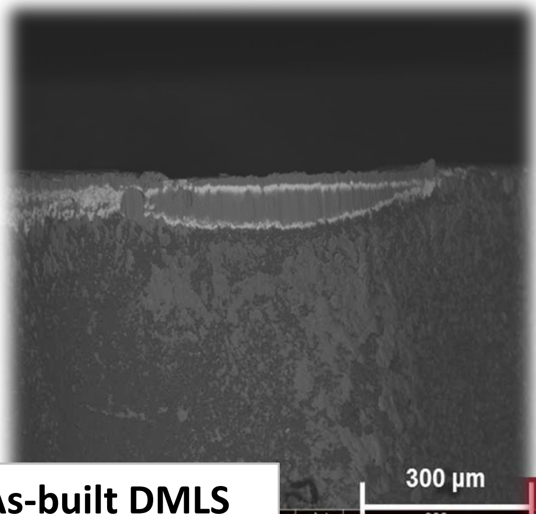




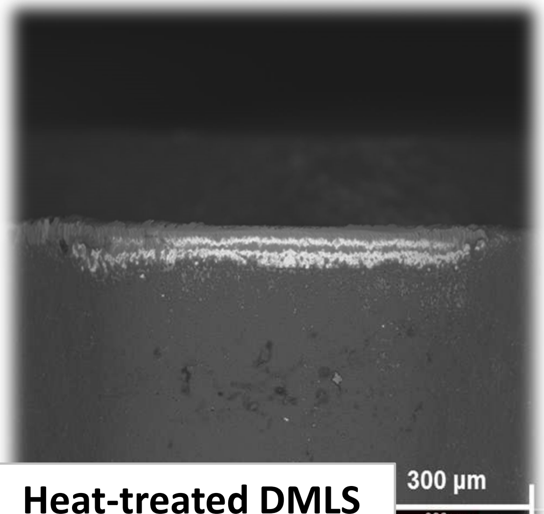
Flank wear

- ✓ Max flank wear again for the as-built DMLS under dry cutting
- ✓ Cryogenic cooling reduces the flank wear regardless the Ti6Al4 microstructure, being the as-built DMLS the microstructure provoking the highest flank wear

Ti6Al4V	Flank wear Vbc [μm] Dry cutting	Flank wear Vbc [μm] Cryogenic cooling
Wrought	76.1±3.2	65.2±4.7
EBM	75.9±4.7	60.2±3.6
As-built DMLS	85.4±2.4	72.7±4.9
Heat-treated DMLS	74.6±4.9	69.9±2.9



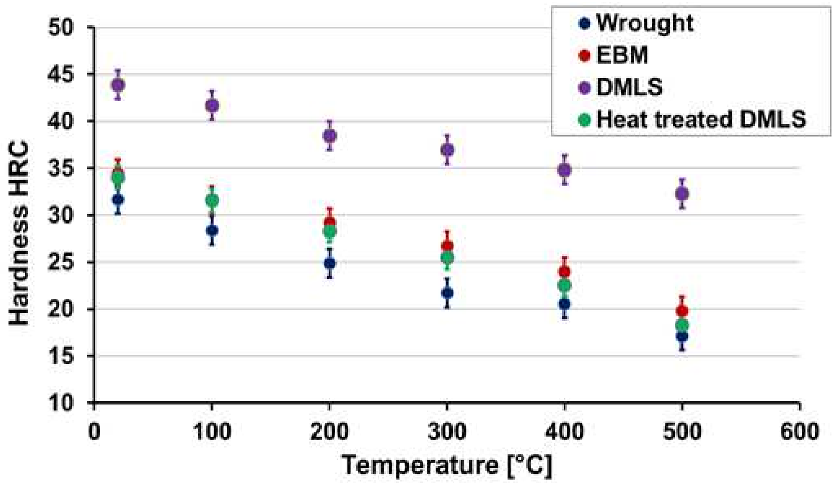
As-built DMLS

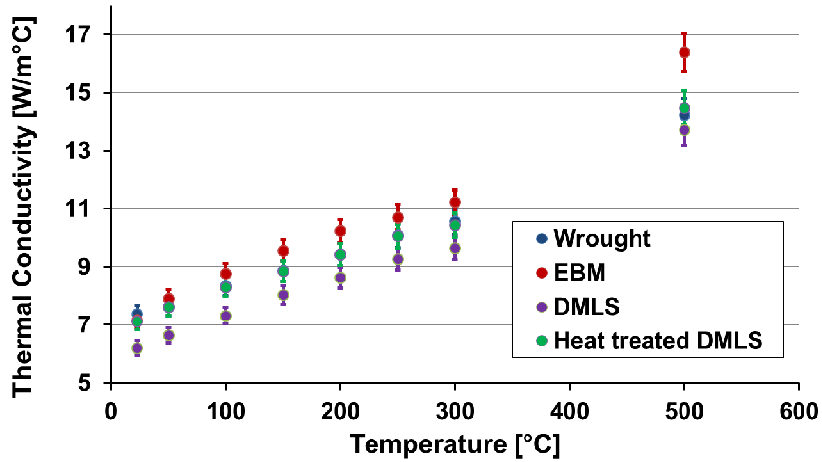


Heat-treated DMLS

Discussion

➔ Correlation between the mechanical and thermal characteristics of the Ti6Al4V microstructures ***at varying temperature*** and the tool wear mechanisms

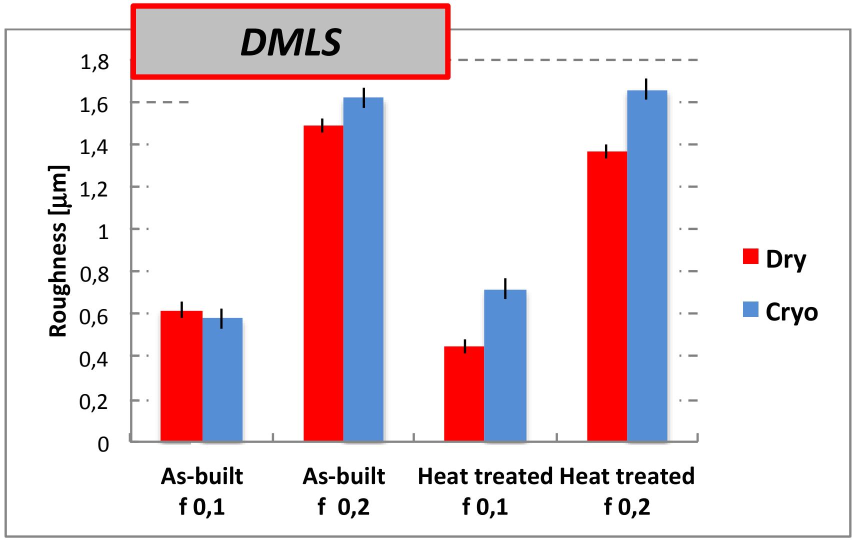


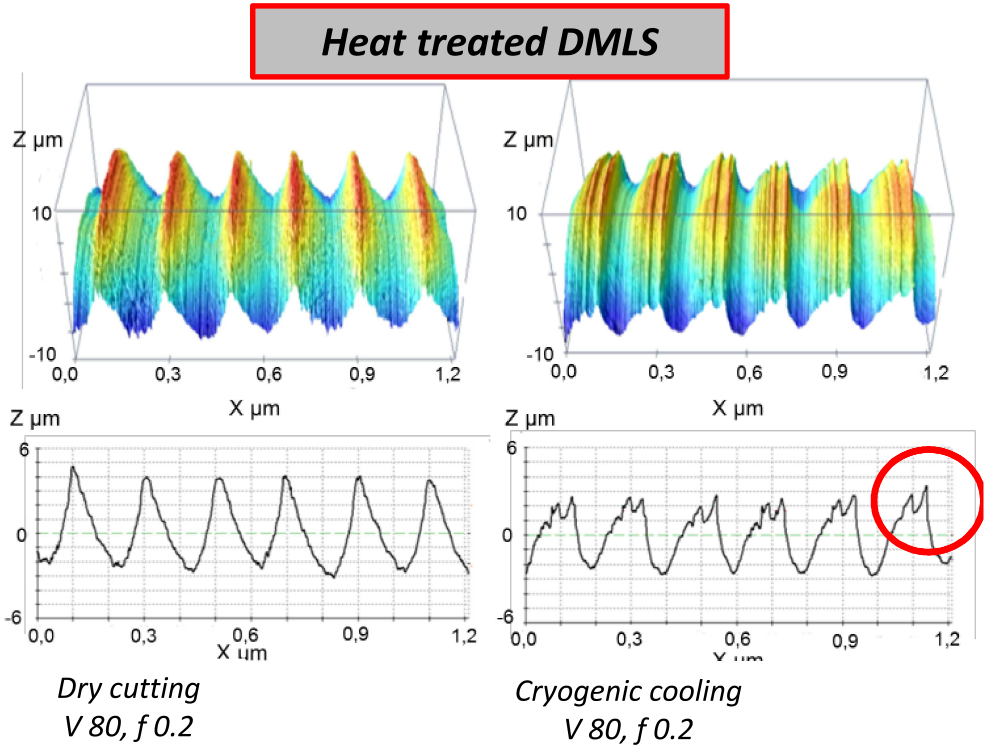


Dry cutting	As-built DMLS	↑↑ Hardness -> ↑ Abrasion	↓↓ Th conduc -> ↑ Diffusion	↑↑ Crater wear
	EBM	↓ Hardness -> ↓ Abrasion	↑↑ Th conduc -> ↓ Diffusion	↓ Crater wear
Cryogenic cooling	As-built DMLS	↑↑ Hardness -> ↑ Abrasion	//	↑↑ Crater wear

Surface topography – DMLS vs. ht DMLS

- ✓ Lower surface roughness in case of dry cutting for the heat treated DMLS compared to the as-built DMLS
- ✓ Slightly higher surface roughness in case of cryogenic cooling for the heat treated DMLS

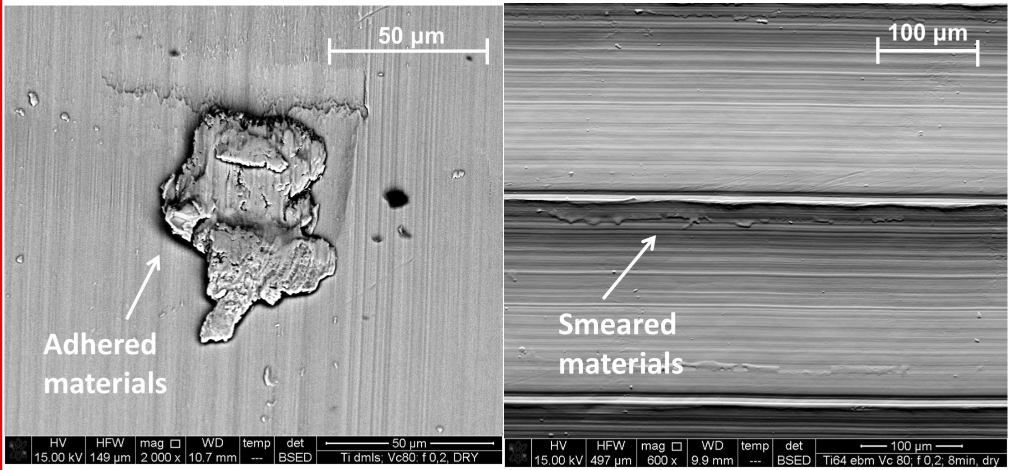




- ✓ Cryogenic cooling produces a more discontinuous surface compared to dry cutting
- ✓ Presence of <u>double feed marks</u> in cryogenically machined samples

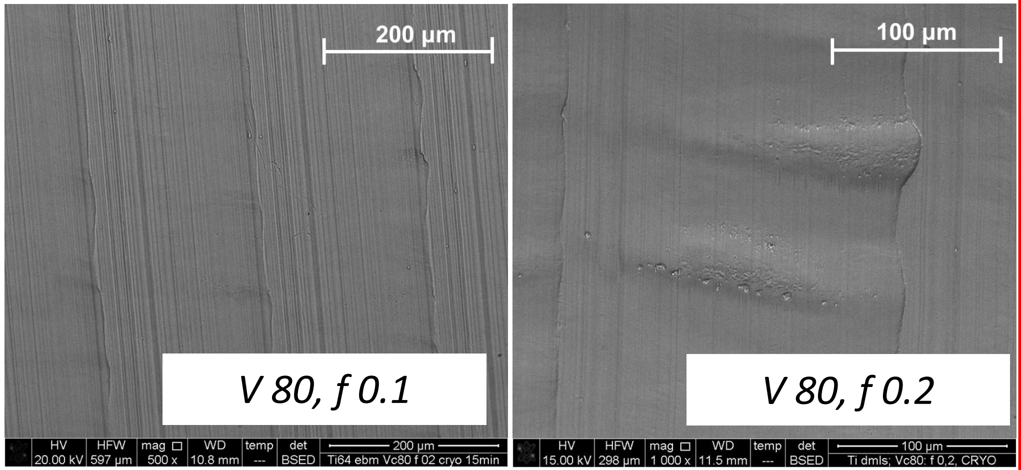
Surface defects – DMLS vs. ht DMLS /1

Dry cutting



- ✓ Defects in ***dry cutting*** mainly due to the temperature increase, i.e. adhered material and side flow
- ✓ Increase of surface defects density at increasing feed rate

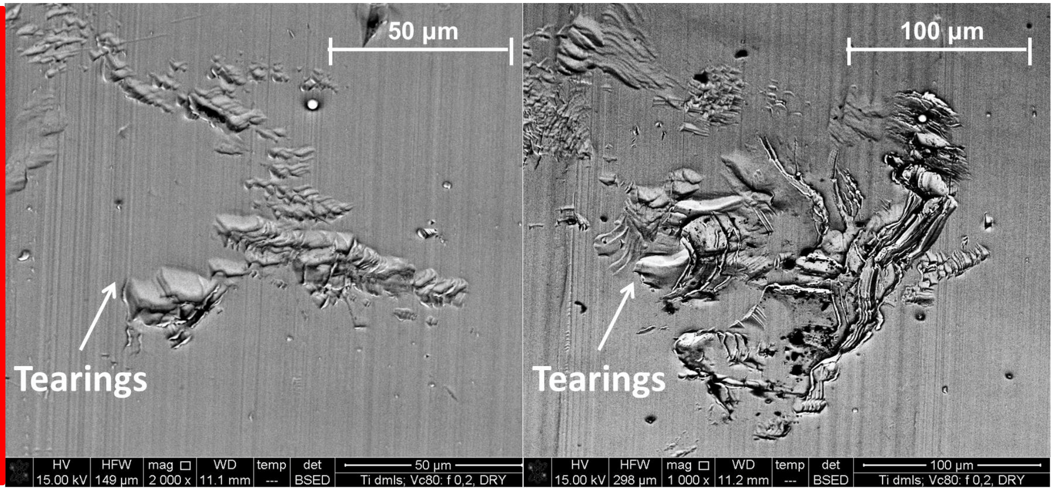
- ✓ Defects in ***cryogenic cooling*** mainly comprise feed marks irregularities, but with the disappearance of the defects typical of dry cutting



Cryogenic cooling

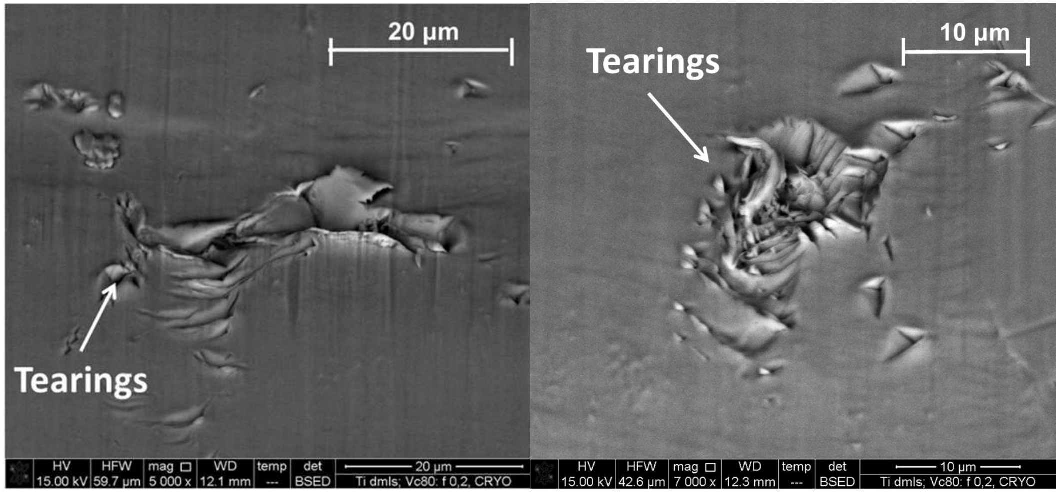
Surface defects – DMLS vs. ht DMLS /2

Dry cutting



- ✓ Defects in the ***as-built DMLS*** comprise also tearings, regardless the cutting strategy, whereas the heat-treated DMLS does not show

- ✓ Cryogenic cooling improves the surface quality for the as-built DMLS with a reduction of the defects density of an order of magnitude



Cryogenic cooling

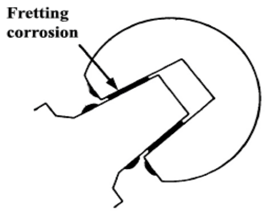
3° ISSUE

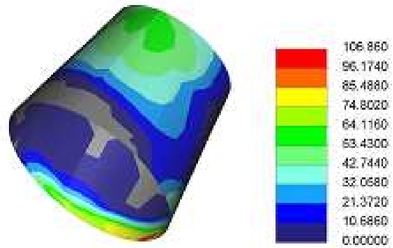
→ Which is the effect of cryogenic machining on the AM material in-service tribo-corrosion behaviour?

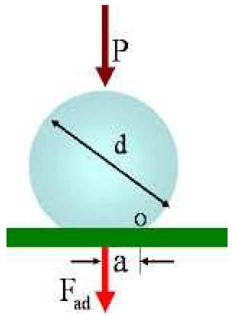
Baseline: dry cutting

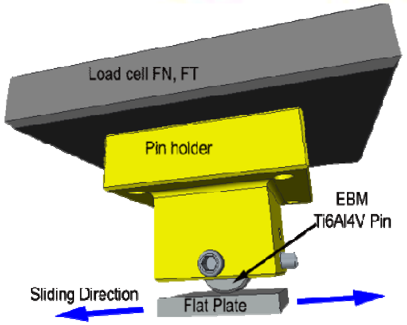
Case study: EBM Ti6Al4V

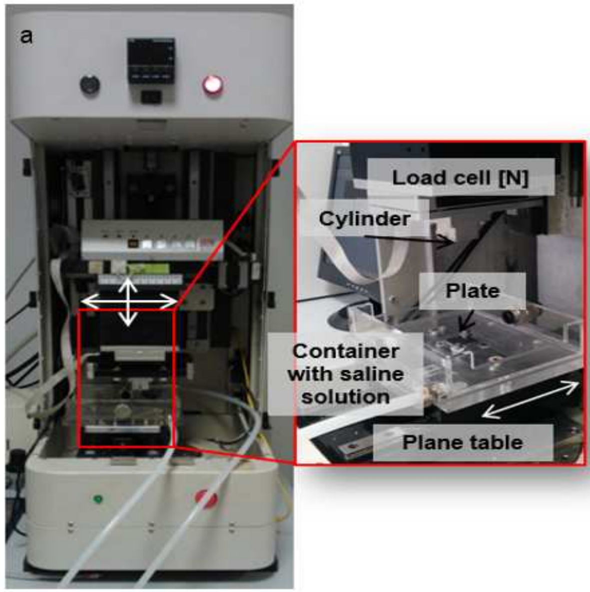
Reciprocating sliding wear /1

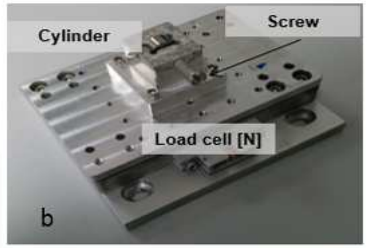


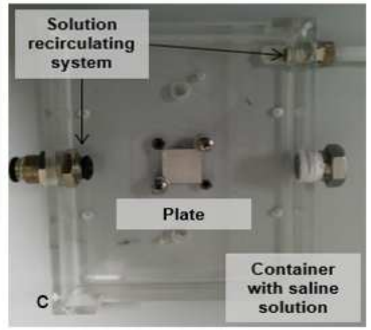


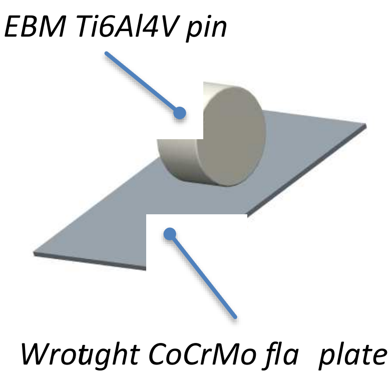






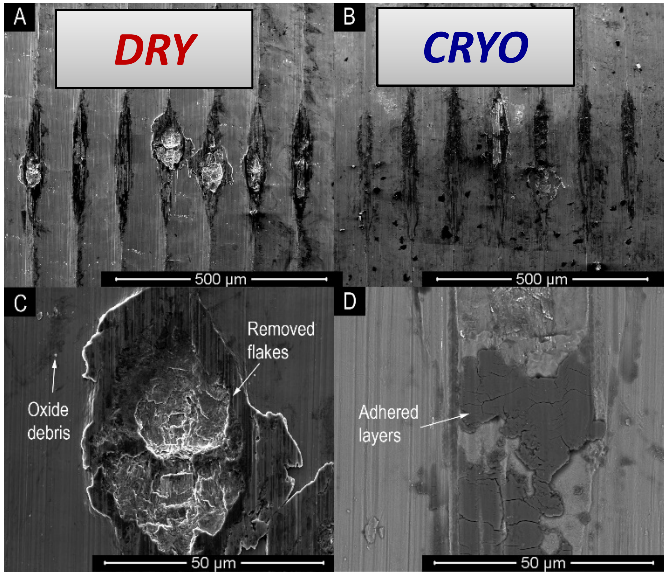


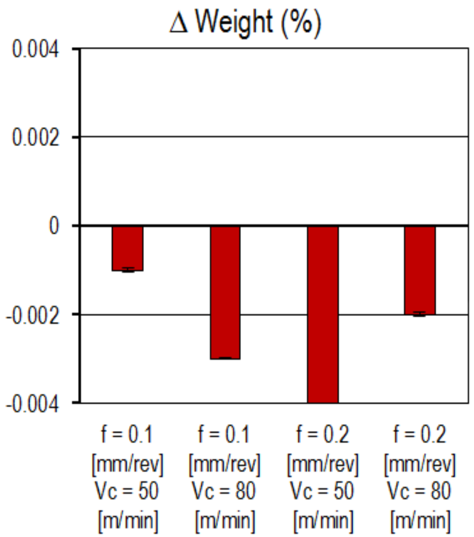


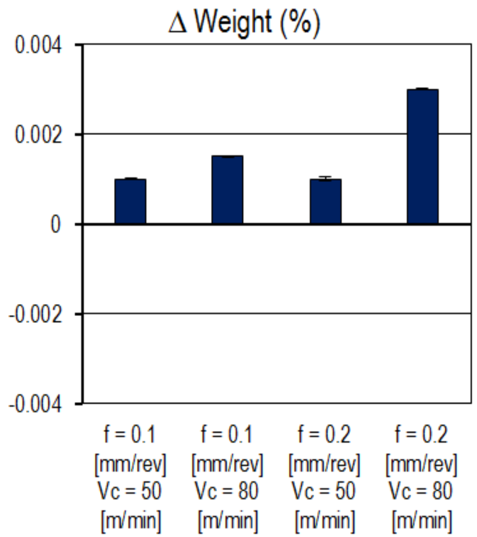


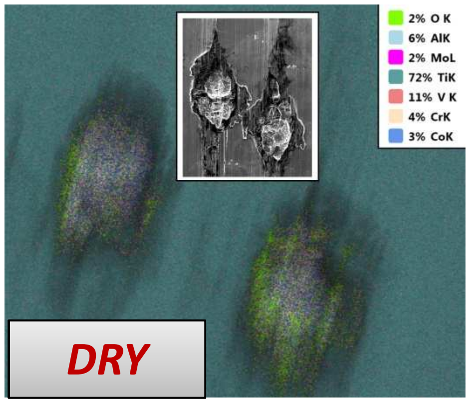
Environment	0.9% NaCl solution
Temperature	37 ± 1°C
Displacement	100 µm
Frequency	1 Hz
Duration	3600 s
Load	18 N

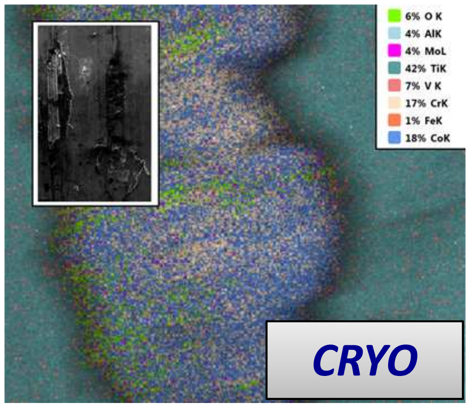
Reciprocating sliding wear /2





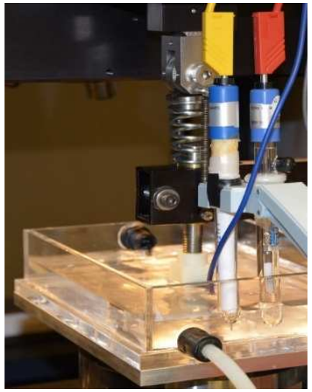


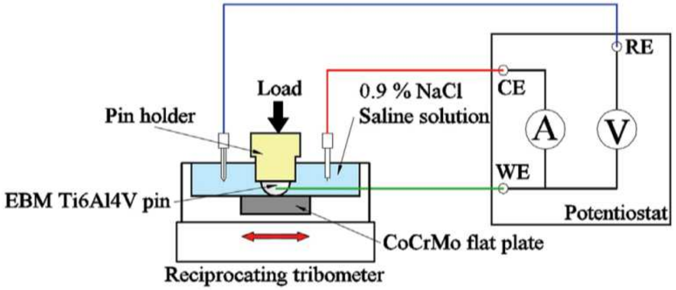


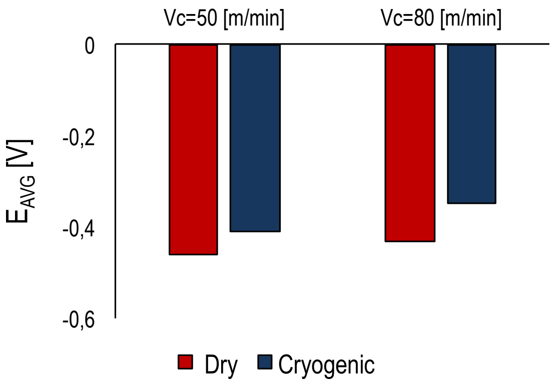


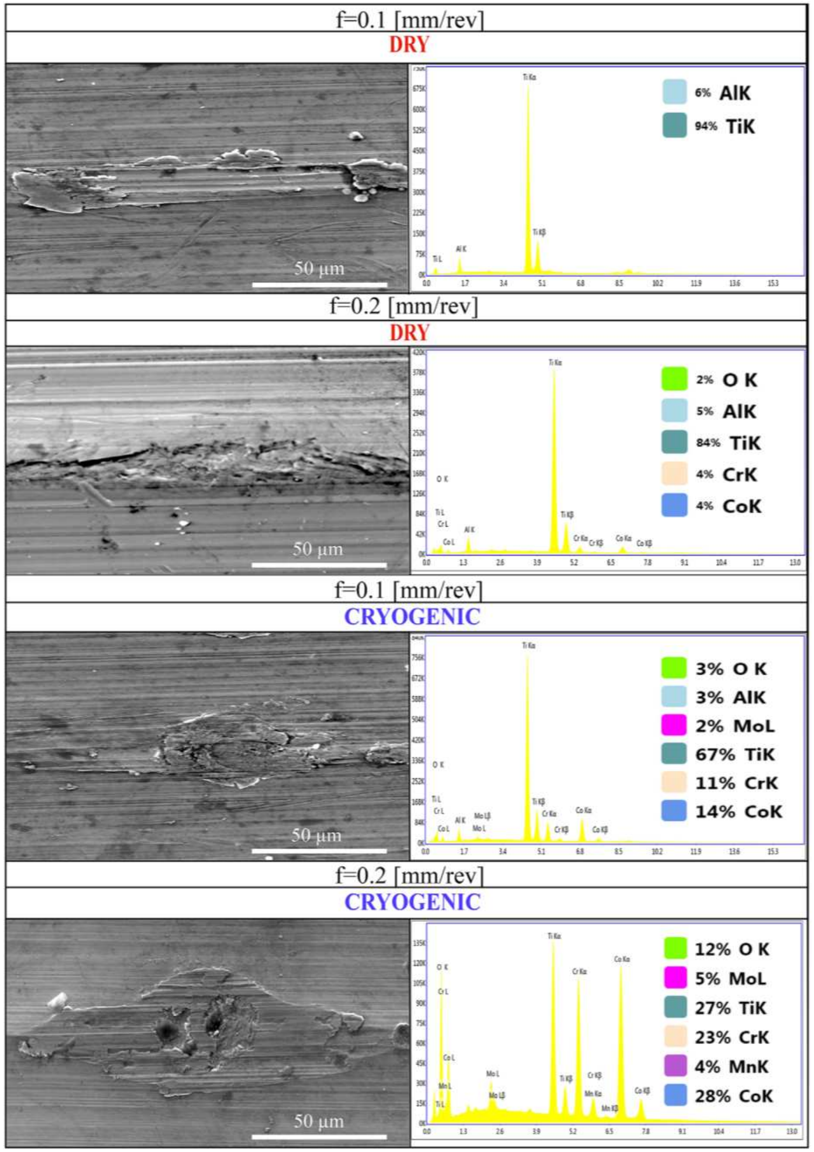
- ✓ Wider and more fragmented scars under dry cutting conditions
- ✓ Severe adhesion of the flat plate material protects the pins against further abrasion in the case of cryogenic machined pins
- ✓ Worn cryogenic machined pins increased in weight due to the adhered flat plate material

Fretting









- ✓ Cryogenic samples show lower corrosion potential than the dry ones
- ✓ Higher adhesion of the counterpart material on the cryogenic samples

Thanks for the kind attention!

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